

Multi Band Gap High Efficiency Converter (RAINBOW)

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1. Introduction

Solar photovoltaic arrays are the most widely used form of energy conversion for powering all types of spacecraft. They are reliable, well understood, and adequate for most space applications. The principal drawback of solar arrays is their relatively high cost, with their relatively high mass being second. Both of these factors could be overcome if the overall array power conversion efficiency were to be significantly increased. For terrestrial applications, mass is less important, but efficiency and especially cost are more important.

State of the art solar arrays utilize only a limited portion of the incident solar spectrum, wasting the remainder of the input energy. This is because a solar cell can only generate current if the wavelength of the incident light is greater than the band gap energy of the semiconductor. In other words, the incident photons must have enough energy to promote electrons out of the conduction band of the semiconductor. Furthermore, for wavelengths with energies much greater than the band gap, the excess energy cannot be utilized. Thus even high quality cells with high quantum efficiencies, such as GaAs, exhibit relatively modest conversion efficiencies, since they cannot respond with high quantum efficiencies to more than a relatively small portion of the incident spectrum. For example, Fig. 1 shows the portions of the solar spectrum to which a GaAs cell and a Si cell can respond. The AMO (space) and AM1.5 (terrestrial) solar spectra, along with a reference spectrum of a 6000 K black body, are taken from Ref. 1.

Many proposals have been made to increase solar array efficiency by using two or more cells with appropriately spaced band gaps to span a greater portion of the incident spectrum. The leading candidate technique to implement this is a vertically-stacked configuration in which two dissimilar band gap cells are stacked atop one another. This creates, in effect, a vertically stacked array. This can be used with or without optical concentration, and requires no spectral filter, since the wavelengths not usable by the top cell pass through and can be absorbed by the bottom cell. The methods have been discussed in detail in the literature and a wide variety of experimental stacked cells have been developed, primarily two-junction but also three-junction cells (for example, Refs. 2-4). Presently, several different industry, university and national laboratory groups are pursuing the stacked-cell approach for two- and three-junction stacks. This technique is nearing in-space demonstration in the SCARLET solar array being developed by BMDO, NASA-LeRC and JPL for the New Millennium program. It has the disadvantage that it is very difficult, if not impossible, to implement more than three different band gap cells in the stacked cell scheme. This is particularly true in the case where the cells are grown as a monolithic stack.

The alternative technique is to split the solar spectrum and focus each portion on a different cell band gap. Each band gap is selected to best match the input spectral portion and thus obtain maximum efficiency. This technique was first conceived by Wade Blocker (Ref. 5) and an array based on the concept was studied and reported by Ivan Bekey (Ref. 6). The general results at the time were that very high array efficiencies were indeed attainable, and that the reduced thermal loads produced further beneficial effects. However, these were partially offset by the large losses of the then-current optical systems to attain the spectral separation. In addition, the mass of the spectral system was such that the overall mass efficiency of the array suffered. Thus, though interesting, the advantages of the technique in terms of the ultimate measures of merit of a solar array, such as watts/m², watts/kg, and dollars/watt, showed significant but not revolutionary advantages relative to actual planar arrays or projections for vertically stacked arrays.

As is true for many advanced concepts, technology advances make it appropriate and highly desirable to periodically reexamine the conclusions. This paper reports on the reexamination of the spectrally split, individually matched cell approach using modern-day optics and lightweight structures. The system concept is illustrated for three different band gaps in Fig. 2. It uses an optical concentrator, a collimator, a number of dichroic filters, each with an appropriately designed passband, and cells which are band gap matched to the passbands, one band gap per spectral region. For most band gaps, actual measurements on real cells with different band gaps are incorporated. For band gaps for which optical and electronic, but solar photovoltaic data are not available (such as above 2 eV), performance estimates are based on actual material data and derated as needed to account for stages of development and real materials issues. In addition, the overall system efficiencies are also projected and account for all anticipated losses. This is called the RAINBOW system concept because it can be readily extended to a larger number of cell band gaps. In this paper, it will be shown that this concept has major advantages over other classes of solar photovoltaic arrays.

2. Performance Modeling (Cell Level Projections)

A. Selection of a Voltage-Matched System

In a multifunction configuration, cells of different band gaps can be either current-matched or voltage-matched. The voltage-matched option was selected, based upon the original voltage-matching concept developed at Sandia National Laboratory (Ref. 7). In a voltage-matched system, electrical connections are made at the module level rather than at the cell level. Cells of the same band gap are wired into series strings. Strings of cells of different band gaps are then wired in parallel. Each individual string provides the same output voltage. The lower band gap cells are each physically smaller, to allow more cells in series; because their voltages are lower, they are connected into longer series strings. Finally, individual cells of different band gaps do not have to be physically stacked. Further details of the concept are provided in Ref. 7.

There are several advantages of voltage-matching relative to current-matching.

- Voltage matching can be done to allow each cell to be operated near its own individual P_{\max} . This is a major advantage over current-matched systems in which the entire system operates at the same V_{\max} , and the overall current is limited by that of the weakest cell.
- The different band gaps are electrically independent. This can be a major advantage if one type of cell degrades faster than another, such as under the electron or proton radiation of the natural space environment, under thermal cycling, or under ultraviolet irradiation.
- With voltage matching, each series string feeds the same voltage into the power processing hardware. This is significantly easier for the power processing hardware to handle than the alternative of current matched strings at different voltages, which, at a given light input, requires “dumping” excess current from the most efficient cells. Alternatively, current matching requires bandwidth division so that each cell produces equal current; this is very difficult to implement.
- Incorporating a relatively large number of band gaps, if desired, is more straightforward. This is a significant contrast to current-matched monolithic systems where the feasible number of band gaps is typically limited to about three.

B. Band Gap and Efficiency Calculations

The JPL computer model calculated optimum band gaps for a system with different numbers of band gaps. It was based upon Willson’s AMO solar spectrum (136.8 mw/cm^2 total, Ref. 8). The spectrum was divided into 100 increments, starting at 0.205 μm and ending at 2.95 μm , covering 134.3 mw/cm^2 (98.2%) of the total. The remaining 1.8% lies at wavelengths beyond 2.95 μm . Each increment is expressed as function of flux (mw/cm^2) and integrated intensity up to that wavelength (mw/cm^2).

Each cell band gap was assumed to cover a specific increment of the AMO spectrum. Parallel calculations were performed for two cases: first, where each band gap accommodated an equal number of the 100 steps in the AMO spectrum, and second, where each band gap accommodated an equal integrated intensity slice of the AMO spectrum. Both cases would be equally straightforward to implement in a real system. The calculated efficiencies for the second case were slightly higher and are detailed below.

A spectrum splitter provides increments of the AMO spectrum to cells of different band gap, so that each cell is selectively illuminated with a narrow energy band. Hence, the power conversion efficiencies of each individual cell in a spectral splitter system are much higher than they would be under a full AMO spectrum. The highest literature cell efficiency reported under selective illumination is 59% for an $\text{Al}_{0.23}\text{Ga}_{0.77}\text{As}/\text{GaAs}$ heterojunction cell, at laser input intensities up to 54 W/cm^2 at 826 nm (Ref. 9). The second-highest literature efficiency under such conditions is 50% to 55% for a GaAs cell, under AlGaAs laser diode illumination, linked via an optical waveguide, at input intensities of 1 W/cm^2 (Ref. 10).

In the JPL model, these were taken as the highest practical efficiencies for individual cells under bandpass illumination. Lower cell efficiencies, ranging from 25% to 40%, were assumed for cells at less advanced stages of development or with fundamental barriers to high efficiency. Efficiencies of multicell systems, with individual cell efficiencies ranging from 59% to 25% under bandpass illumination, were calculated. The results for individual cell efficiencies of 59% and 50% are presented in Fig. 3. The composite efficiency, for the 59% cells, ranged from 56% (25 band gaps) down to 33% (2 band gaps). Similarly, the composite efficiency for the 50% cells ranged from 48% (25 band gaps) down to 33% (2 band gaps).

The trade between projected performance and practicality yielded an optimum 9 cell system whose composite efficiency was 50% (for the 59% efficient cells) or 42% (for the 50% efficient cells). The calculated performance improvement for a larger number of band gaps was only a few percentage points, and outweighed by the greater complexity of such a system.

The calculated band gaps for this 9 cell system ranged from 3.06 eV down to 0.60 eV. Each band gap was found to correspond closely to a practical material which has been investigated for either photovoltaics (PV), thermophotovoltaics (TPV) or optoelectronics use. Some would need further optimization but no fundamentally new materials development. These materials were:

- 6H-SiC (2.9 eV)
- 3C-SiC (2.2 eV)
- $\text{Ga}_{0.53}\text{In}_{0.47}\text{P}$ (1.95 eV, slightly mismatched to a GaAs substrate)
- $\text{Al}_{0.20}\text{Ga}_{0.80}\text{As}$ (1.71 eV, lattice matched to a GaAs substrate)
- GaAs (1.43 eV)
- $\text{Ga}_{0.87}\text{In}_{0.13}\text{As}$ (1.25 eV, slightly mismatched to a GaAs substrate)
- Si (1.11 eV)
- $\text{Ga}_{0.48}\text{In}_{0.52}\text{As}$ (0.75 eV, slightly mismatched to an InP substrate), and
- $\text{Ga}_{0.36}\text{In}_{0.64}\text{As}$ (0.60 eV, mismatched to an InP substrate).

Additional features used to identify these practical materials included:

- Actual or estimated cell or materials cost.
- . Ease of high quality materials growth.
- . Knowledge and applicability of device processing technology.
- . Availability of high quality substrates, either exactly or closely lattice-matched.
- Capability of substrate to be made thin, if not already lightweight.
- Availability of literature data.
- . Feasibility of a conventional p-n or p-i-n junction cell structure.

The model calculations under bandpass illumination were repeated for a set of three real cells (GaInP, 1.90 eV; GaAs, 1.43 eV; Ge, 0.67 eV) being pursued by industry for monolithic stacks. This was done to verify the overall integrity of the model. Calculated composite efficiencies were 37% (for 59% efficient cells), 31% (for 50% efficient cells), 25% (for 40% efficient cells) and 20% (for 33% efficient cells). These composites are in accord with general industry projections. Typical industry goals are 27 % for a near-term 3-junction stack under 1-sun AMO, 35 % for a long-term 3-junction stack under 1-sun AMO, and 40 % for long-term multifunction concentrators.

C. String Length Calculations

Voltage matching was performed at V_{max} (the voltage at a cell's maximum power point) to determine optimum string lengths for power processing. This was done for an operating temperature of 28°C. In the 9 cell system, the number of cells per string was calculated for each band gap. The goal was 28 V per string, the present NASA/JPL spacecraft bus standard. However, the calculation could be readily extended to higher voltage systems if desired. A diagram of how the nine strings would be connected to form a single electrical output is shown in Fig. 4. The overall diagram is not to scale, but the relative cell sizes are approximately to scale. The number of cells per string ranged from 20 (for 6H-SiC) up to 185 (for $Ga_{0.36}In_{0.64}As$).

Temperature effects have the potential to affect voltage matching. The cell short circuit current (J_{sc}) increases slightly as a function of temperature, whereas V_{oc} , V_{max} and fill factor all decrease as a function of temperature. The dominant variation is that of voltage, and the change with temperature is largest for low band gap cells. For high temperature operation, the strings of low band gap cells would need to be lengthened. Conversely, for low temperature operation, the strings of high band gap cells would need to be lengthened. If there is significant temperature variation during the mission, the strings may move in and out of voltage-matching. For such a mission, the power processing system would need to be designed to address this issue.

3. RAINBOW System Design

A. Concentrator Optics Issues

Losses due to packing factors and concentrator optics included three derating factors:

- 95% cell packing factor for a single-collector system,
- . 95% optics packing factor for a multiple collector system (relative to single-collector), and
- . 90°/0 overall efficiency for concentrator optics (includes reflection and transmission losses).

The concentrator optics factor included losses for cell alignment with optics, chromatic aberration, nonuniform illumination over the cell plane, cell location with respect to

the lens focal length, pointing angle tolerances, and lens defects. The most probable concentrator lens, a Fresnel configuration, is particularly tolerant of defects. Because the factors are multiplicative, the net effect would be to reduce the system efficiency by a factor of 0.812.

Under high concentration, cell efficiencies rise, and cell waste heat losses are reduced. This is partially countered by a "greenhouse effect" limiting frontside radiative cooling through the concentrator lenses. Overall, however, preliminary calculations indicate that a modest cell operating temperature reduction can be achieved. Pointing requirements are also much stricter for high concentration. Hence, the minimum concentration compatible with power output requirements would generally be recommended.

B. Spectrum Splitter Overview

The spectrum splitter is a key part of the system because it provides each cell with a narrow region of the incident solar spectrum which is at or just above the cell band gap energy. The options initially considered were:

- Dichroic beamsplitters, which can provide efficient band isolation. Dielectric-stack coating technology has improved substantially in recent years, particularly in power handling and durability.
- Efficient and highly capable single-order diffractive optics, which have been designed and fabricated at JPL. A thin film dispersive device with prism-like properties (each wavelength goes into a single order) may be feasible for a multi-order system.
- Prisms can provide minimal reflective losses.
- "Flat prisms" have the advantages of low mass and small focal length.
- Total reflection devices,

The two leading candidates at this writing are dichroic beamsplitters and prisms. Most of the effort to date has focused on the beamsplitter filter option. Typical filters can withstand a maximum of about 20X optical concentration, which is acceptable for RAINBOW. Anticipated optical losses due to the filters are being quantified, as is the sensitivity of a filter-based system to offpointing or misalignment. The filter option is described further in section C, below. In parallel, preliminary computer modeling of a prism-based system (John Grievenkamp, University of Arizona) is in progress. There is concern that it will be difficult to sufficiently avoid spectral order overlap with a practicable prism system. A decision on whether to use filters or prisms in the prototype hardware is expected to be made about March 1997.

C. RAINBOW System Level Efficiency Calculations

Initial system level efficiency calculations assumed a linear Fresnel optical concentrator and dichroic filter beamsplitters. Key system trades included: number of

cells and their band gaps, the most effective way to split up the input spectrum, the concentration ratio, mass and cost. Each dichroic filter was assumed to have a reflectance of 100 % above the corresponding cell band gap, a reflectance of 0% below the band gap, and a transition region (0 to 100% reflectance) spanning about 50 nm. The center of the transition region was located at the band gap. Vendor data indicated that the filters could accept up to about 20 suns (20X) input illumination. Because each cell sees only a portion of the input AMO spectrum, the cell operating temperature will be reduced relative to a system without a spectrum splitter. For example, up to 5x concentration provides the same thermal input as a conventional cell under unsplit 1X AMO. This acts to further increase the cell efficiency and is particularly pronounced for lower band gap cells.

The calculations also assumed a Fresnel linear trough concentrator, similar to that currently being used by AEC-ABLE for their SCARLET linear trough optical concentrator system. Efficiencies of 95% were assumed for the concentrator and for each dichroic filter. The general system concept, not to scale, was illustrated in Fig. 2. A collimator may or may not be needed in the final system design. Individual cell data were based on state of the art solar cells, when available, and on the results of single junction cell laser measurements (Ref. 9, 10). Cell data for materials such as GaN and SiC, where solar cells have not yet been fabricated, were estimated, based on comparable data for lower band gap materials and then derated to account for lesser stages of development.

The results of the system calculations, including measured loss factors, for several different three, four and five cell systems are presented in Fig. 5. The optimum systems include four real cells: GaN or 6H-SiC, GaInP, GaAs and Ge. The projected system-level efficiencies are 40.04 % with GaN and 40.30 % with 6H-SiC, a small difference. The overall power densities are 54.74 mw/cm² with GaN and 55.09 mw/cm² with 6H-SiC, also a small difference. It is notable that when system-level effects are taken into account, there is only minimal advantage to further increasing the number of band gaps. However, as individual cell performances continue to improve, particularly at the highest and lowest band gaps, this situation may change, and there may be a more significant advantage to the use of more than 4 band gaps.

D. RAINBOW System Cost Estimate and Measures of Merit

The optical concentrator reduces the overall cost impact of the relatively expensive cells and beam splitters. A preliminary JPL cost estimate was made for a three cell case, including GaInP, GaAs, and Si cells. The cost estimate assumed the total cost of the three component cells to be 1.2 X the cost of an industry stacked multi band gap cell. The estimated cost of the beam splitters was taken as 20% of the cost of the industry stacked multi band gap cell. However, the estimated efficiency of the 3 cell RAINBOW is about 1.3 times that of an industry three junction stacked system, and the estimated area about 25% less than SCARLET's. The net effect is that the cost and mass of a RAINBOW system with three band gaps are comparable to those of industry's

SCARLET stacked-cell concentrator system. RAINBOW, however, can be expanded to a larger number of band gaps.

A more detailed cost estimate for a four (or five) cell RAINBOW system assumed 4 (or 5) cells per concentrator element; cell efficiencies of 50% under spectrally selective illumination; a total of 36 concentrators, each with 90% transmission; each concentrator area 22 in², for a total of 800 in²; an optical concentration ratio of 20 X, and a total output power of 360 W. The total system cost, including the concentrator optics, cells, cell-interconnect-coverglass assembly costs, circuit laydown, dichroics, integration, structural elements and aluminum mirrors, was \$87.4 K, or \$ 250/W, not including environmental testing (e. g. acoustic, vibrational, thermal). Overall, this cost represents a significant improvement relative to comparable costs for state of the art one-sun and concentrator space solar arrays. The cost estimate process is continuing to be refined. Finally, the RAINBOW four cell system (as described in Fig. 5, with GaN or 6H-SiC, GaInP, GaAs and Ge cells) was compared to state of the art alternatives (Fig. 6). Measures of merit were dollars per watt (\$/w), watts per kilogram (w/kg) and watts per square meter (w/m²). The state of the art arrays were Si planar, GaAs planar and SCARLET linear concentrator with GaInP/GaAs cells. This general overview indicates that RAINBOW could potentially provide significant increases in measures of merit, relative to conventional photovoltaic arrays.

In these measures of merit, it should be noted that the cost data, in particular, is highly mission specific. It involves the power level of the array, cell laydown complexity, acceptance testing requirements, and related factors. The data in Fig. 6 also assume mature technologies. End of life (EOL) costs per watt will favor cell systems with reduced degradation rates, in general increasing the cost of Si arrays with respect to other designs. Concentrator systems are expected to have the least cost growth for EOL conditions. Also, comparisons of this type are not absolute indicators of a particular cell system's value. More accurate comparisons need to include highly mission specific requirements, such as radiation environment, lifetime, cell laydown complexity (shadowing, keep out zones, etc.), acceptance test requirements, and related factors,

The measures of merit included here are for BOL (beginning of life) values, and do not include factors particular to any specific mission. Geosynchronous altitude is assumed for these comparisons, with BOL power levels are assumed to be in the range of 2-5 kW. Rigid substrate array technology is assumed for all designs. Flexible substrate deployable systems are not included, even though they can achieve very high specific performance (w/kg), on the order of 80-100 w/kg, with planar designs. Such lightweight systems tend to have higher radiation degradation than the rigid substrate designs, thereby making BOL comparisons inaccurate. It is expected that concentrator/rigid substrate designs will satisfy different mission requirements than flexible lightweight designs. The importance of the BOL/EOL discrepancies can be also seen in cost estimates. For example, silicon solar arrays are in general, significantly less costly (\$/w) than GaAs arrays. Yet, when actual mission requirements and degradations are included, the GaAs design proves more cost effective. This is evidenced in the recent emphasis on GaAs cell production by the cell manufacturers.

E. RAINBOW Demonstration Hardware

The first set of demonstration hardware for the RAINBOW concept has been designed. Fabrication is planned during early 1997, with completion expected by about March 1997. The hardware will include linear concentrator optics and several different cell band gaps. It will be fabricated for JPL by NASA-LeRC and Entech Corporation. The second set of demonstration hardware will add a spectrum splitter and include 3 to 4 cell band gaps. Design will take place during early 1997, and it is expected that the hardware will be fabricated during mid-1997.

SUMMARY

The RAINBOW multi band gap system represents a unique combination of solar cells, concentrators and beam splitters. The use of separate cells offers the widest possible scope of material choices. Many different component combinations are possible. The relatively low temperature operation, due to reduced thermal input per cell, adds to the performance increase. Finally, RAINBOW is a flexible system which can readily expand as new high efficiency components are developed. Based on data for real cells and optical components, RAINBOW is expected to convert over 40% of incident solar energy to electricity at the system level. This conclusion is based on preliminary analyses of cell and optics performances. These calculations indicate that system performance is very sensitive to component parameters. At this stage, it has been necessary to assume many of these parameters based on manufacturers data, and estimates of near term technology improvements. The initial assumptions will be reviewed in the coming months, and breadboard model hardware will be used to obtain quantitative performance measurements that can be used to "calibrate" the system performance model. Fabrication of the breadboard model hardware is expected to take place during early to mid 1997.

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Figure Captions

Fig. 1. Portions of the solar spectrum for which the internal quantum efficiency of a GaAs cell and of a Si cell exceed 80%.

Fig. 2. Spectrally split, individually matched cell approach using dichroic filters for spectrum splitting. Illustrated for three cell band gaps.

Fig. 3. Composite efficiencies for a large number of cell band gaps under selective illumination.

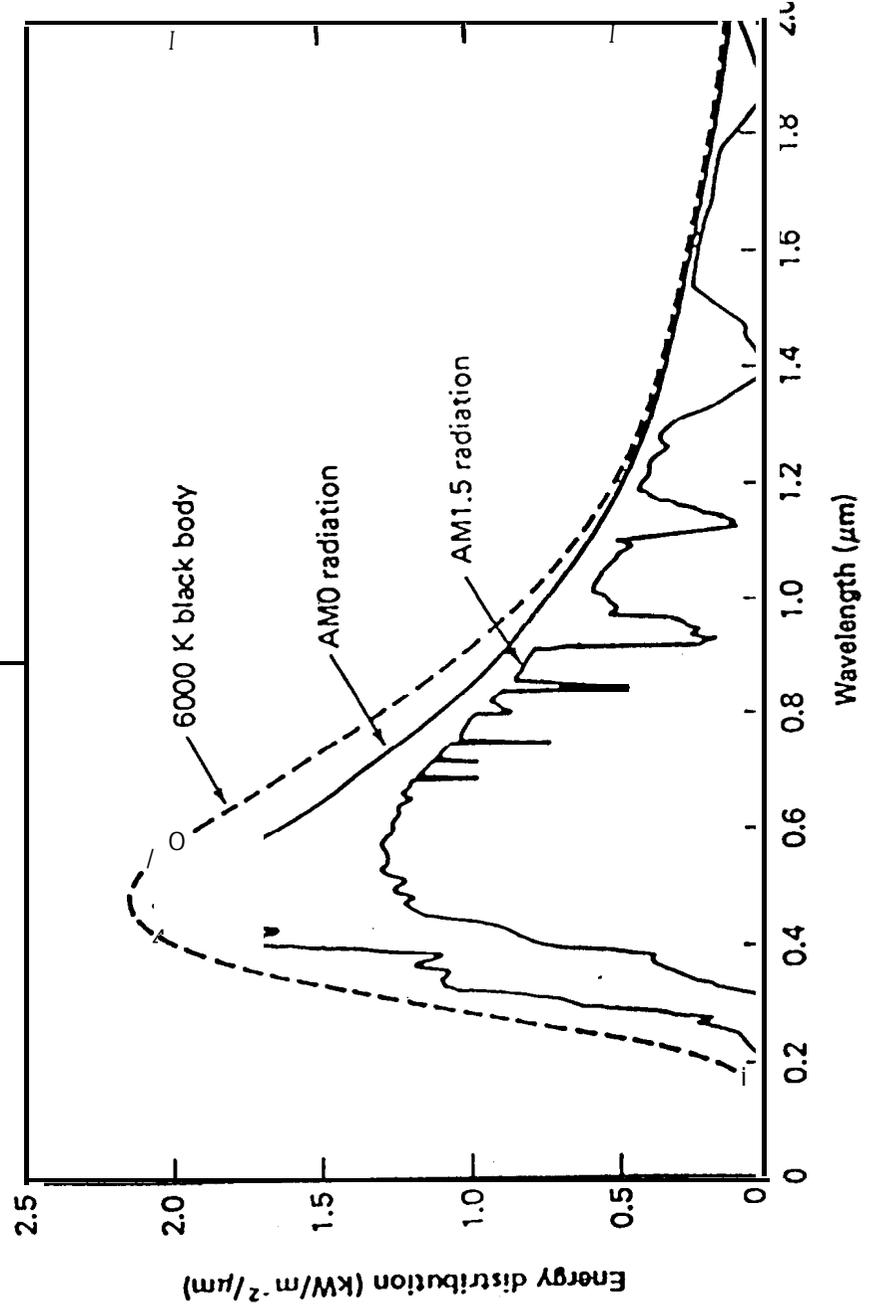
Fig. 4. Voltage matching scheme for the cell strings in the 9 band gap system.

Fig. 5. Calculated system level efficiencies for RAINBOW designs ranging from 3 to 5 cell band gaps,

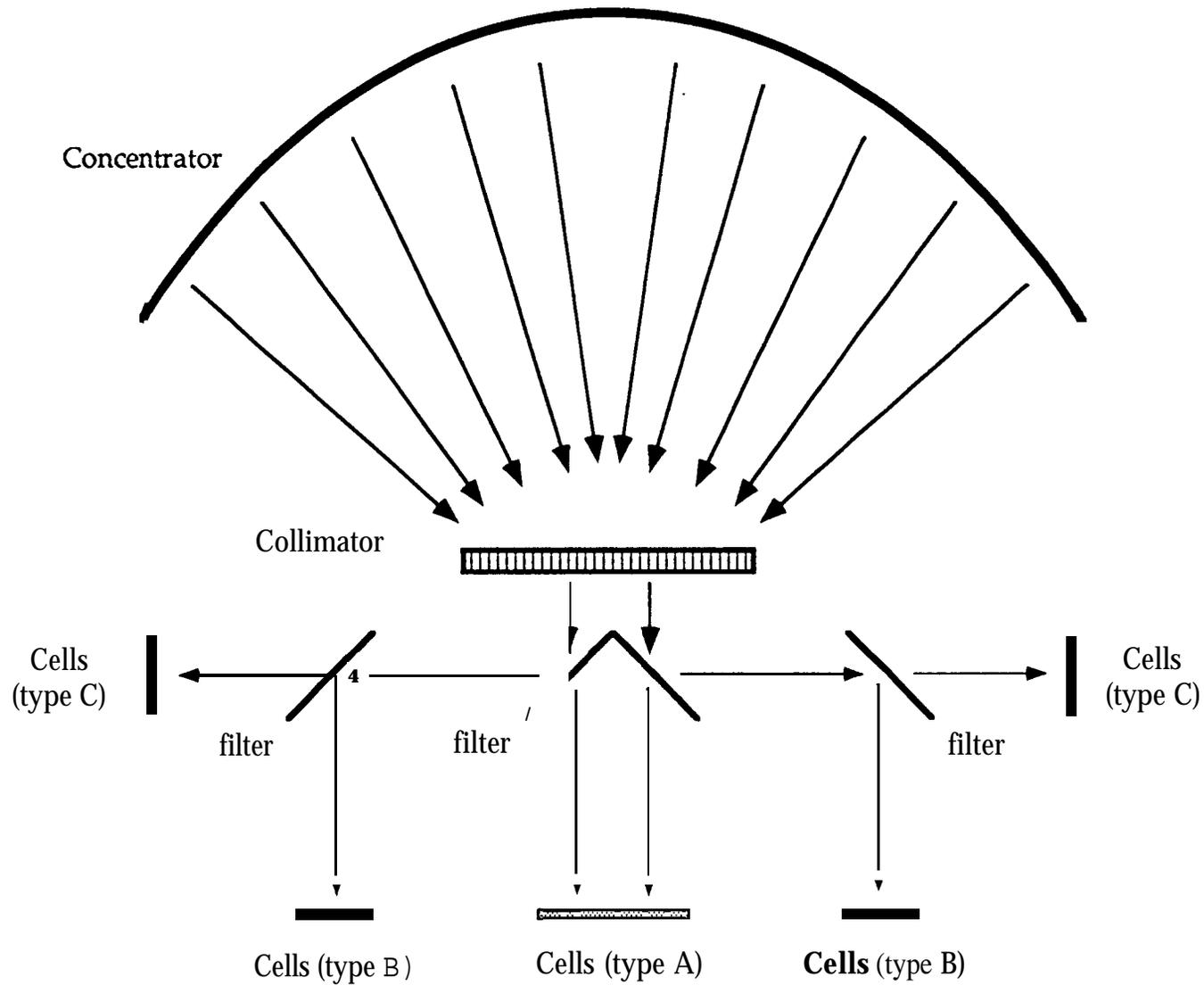
Fig. 6. Comparison of the RAINBOW four cell system to state of the art solar array alternatives.

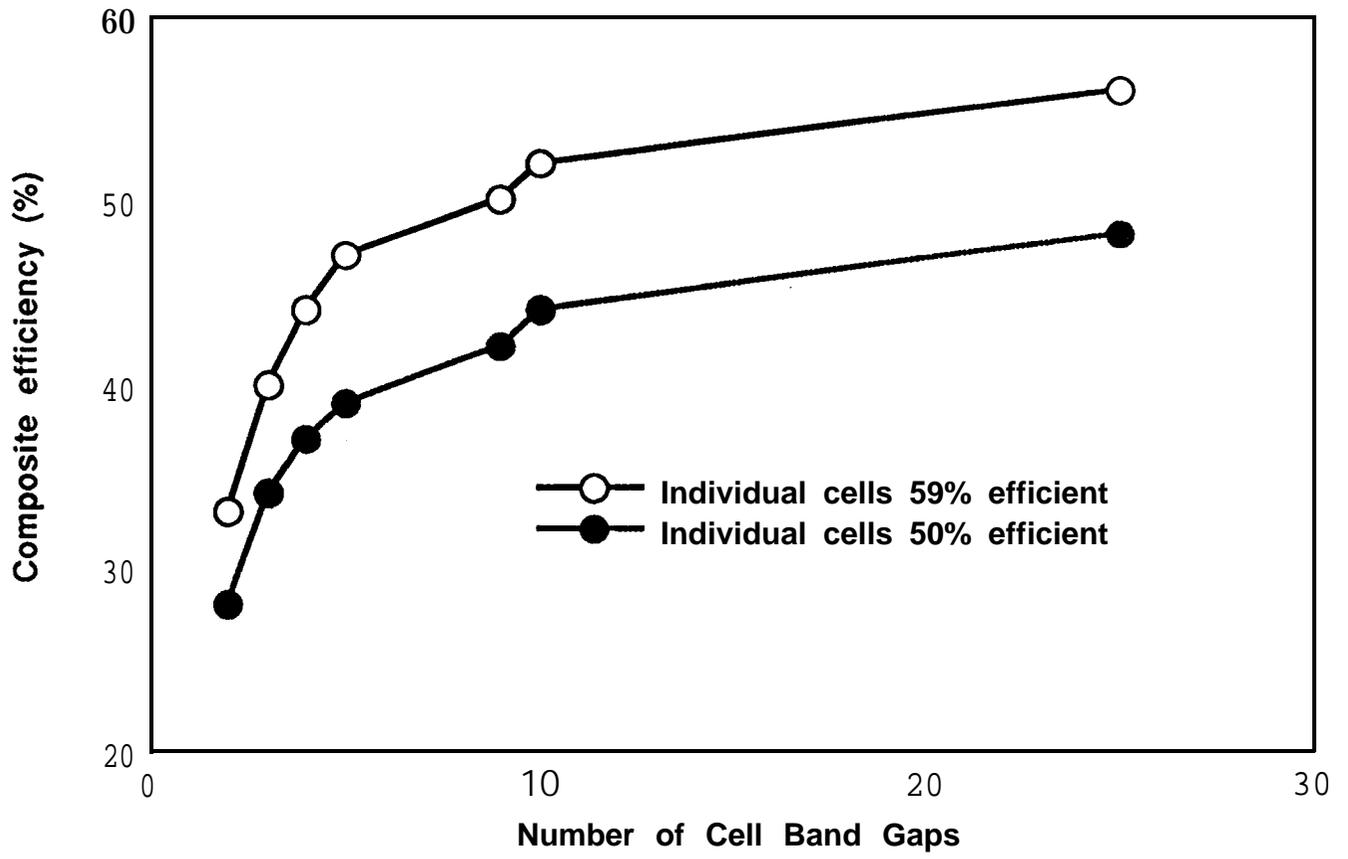
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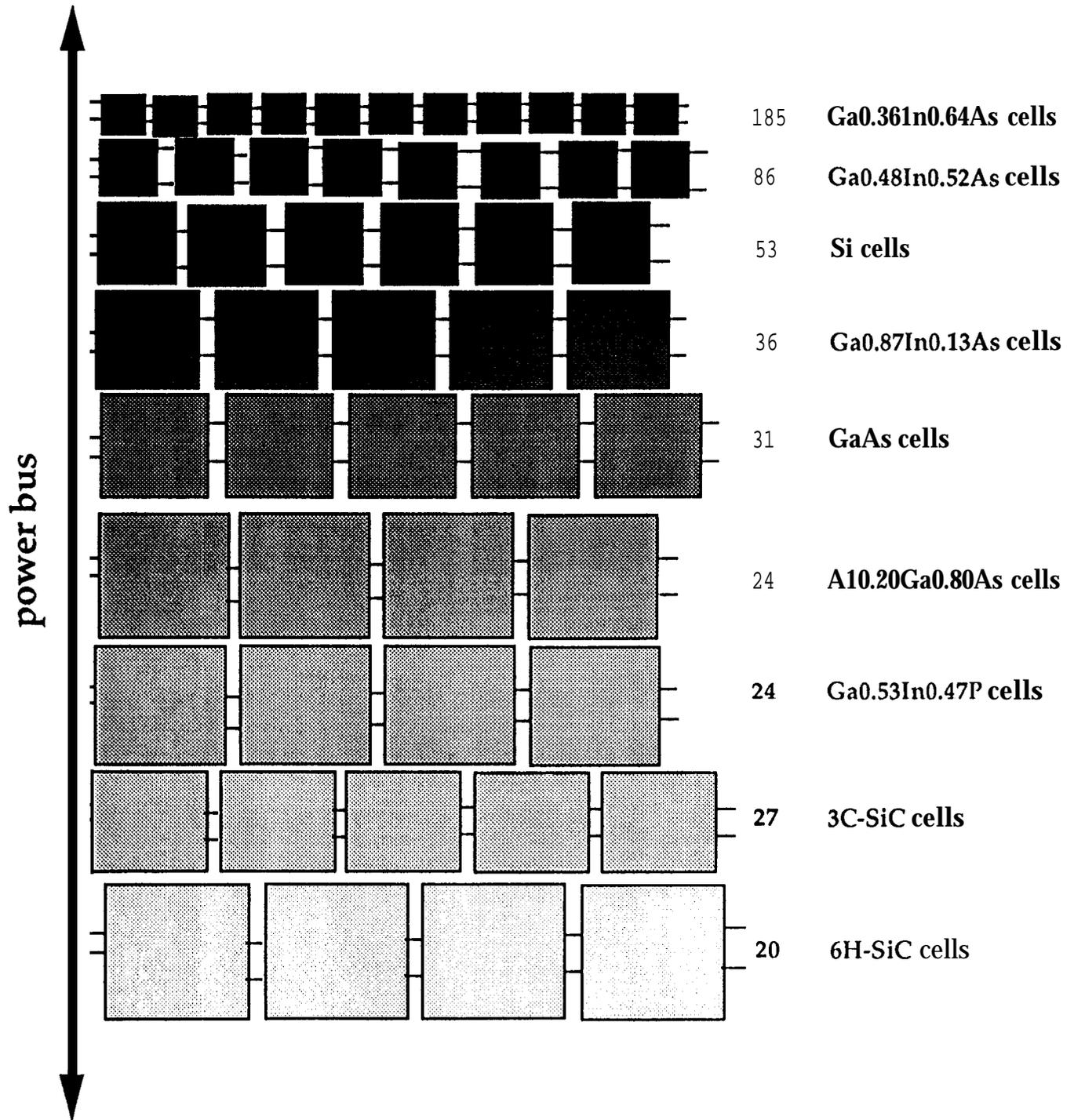
Multi-spectral Solar Array Concept



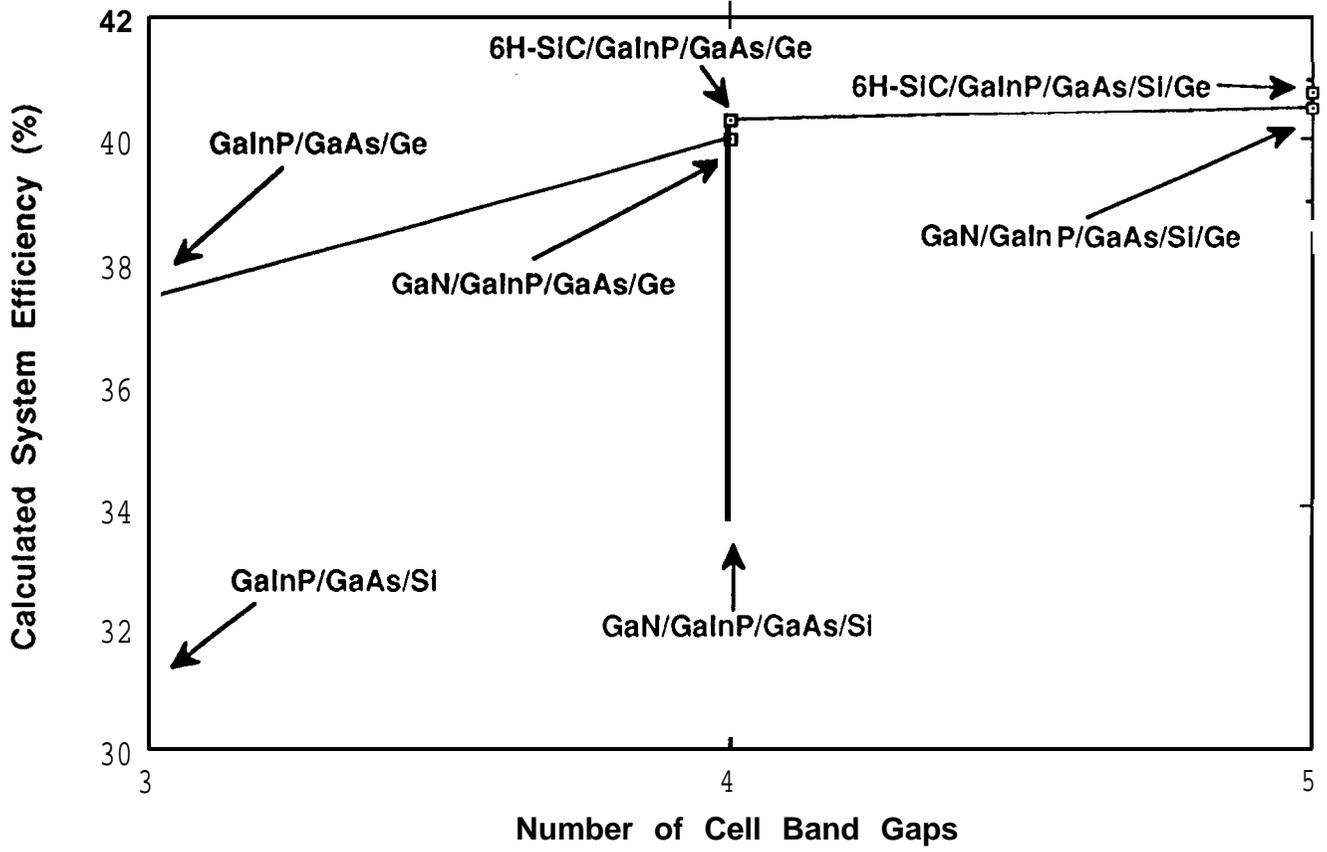


VOLTAGE MATCHING SCHEME (NOT QUITE TO SCALE)

STRINGS SHOWN TRUNCATED FOR ILLUSTRATION



System Efficiency vs. Number of Cell Band Gaps



	Si Array	GaAs/Ge Array	GaInP/GaAs Array (SCARLET)	RAINBOW 4 Cell Array
\$/w (Note 1)	1	1.2	1	1
w/kg (Note 2)	40	40	45	60 (estimated)
w /m² (Note 3)	145	190	190	300 (at 40% system efficiency)

Note 1: **Relative costs for BOL**, including recurring costs.

Note 2: For rigid panels, not including solar array drive mechanisms, at beginning of life (**BOL**)

Note 3: At operating temperature in geosynchronous orbit (**GEO**)